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Abstract
During the last 30 years, environmental issues about the chemical and biological contaminations of water have become a major concern for society, public authorities and the industry. Most domestic and industrial activities produce wastewaters containing undesirable toxic contaminants. In this context, a constant effort must be made to protect water resources. Current wastewater treatment methods involve a combination of physical, chemical and biological processes, and operations to remove insoluble particles and soluble contaminants from effluents. This article provides an overview of methods for wastewater treatment, and describes the advantages and disadvantages of available technologies.

Keywords Wastewater treatment · Contaminants · Pollutants · Effluents · Technologies available

Introduction

Actually, water pollution by chemicals has become a major source of concern and a priority for both society and public authorities, but more importantly, for the whole industrial world (Sonune and Ghate 2004; Crini 2005; Cox et al. 2007; Sharma 2015; Rathoure and Dhatwalia 2016). What is water pollution? Water pollution can be defined in many ways. Pollution of water occurs when one or more substances that will modify the water in negative fashion are discharged in it. These substances can cause problems for people, animals and their habitats and also for the environment. There are various classifications of water pollution (Morin-Crini and Crini 2017). The two chief sources can be seen as point and non-point. The first refers to the pollutants that belong to a single source such as emissions from industries into the water, and the second on the other hand means pollutants emitted from multiple sources.

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The causes of water pollution are multiple: industrial wastes, mining activities, sewage and waste water, pesticides and chemical fertilizers, energy use, radioactive waste, urban development, etc. The very fact that water is used means that it will become polluted: any activities whether domestic or agricultural but also industrial produce effluent containing undesirable pollutants which can also be toxic. In this context, a constant effort must be made to protect water resources (Khalaf 2016; Rathoure and Dhatwalia 2016; Morin-Crini and Crini 2017).

The legislation covering liquid industrial effluent is becoming stricter, especially in the more developed countries, and imposes the treatment of any wastewater before it is released into the environment. Since the end of the 1970s, in Europe, the directives are increasingly severe and zero rejection is being sought by 2020. Currently, the European policy on water results from the Water Framework Directive of 2000 which establishes guidelines for the protection of surface water, underground water and coastal water in Europe (Morin-Crini and Crini 2017).

The Water Framework Directive also classified chemicals into two main lists of priority substances. The first, the "Black List," involves dangerous priority substances considered to be persistent, highly toxic or to lead to bioaccumulation. The second list, the "Grey List", gathers priority substances presenting a significant risk for the environment. The selection of these substances can either be based on individual substances of families of substances (e.g., metals, chlorobenzenes, alkylphenols) or on the basis of the industrial sector (e.g., agro-food industry, chemicals industry, metal finishing sector). Currently, Europe is now asking industrials to innovate, to reduce and/or eliminate the release of dangerous priority substances and priority substances in their wastewaters. Moreover, recycling wastewater is starting to receive active attention from industry in the context of sustainable development (e.g., protection of the environment, developing concepts of "green chemistry," use of renewable resources), improved water management (recycling of waste water) and also health concerns (Kentish and Stevens 2001; Cox et al. 2007; Sharma and Sanghi 2012; Khalaf 2016; Rathoure and Dhatwalia 2016; Morin-Crini and Crini 2017). Thus, for the industrial world, the treatment of effluents has become a priority.

During the past three decades, several physical, chemical and biological technologies have been reported such as flotation, precipitation, oxidation, solvent extraction, evaporation, carbon adsorption, ion exchange, membrane filtration, electrochemistry, biodegradation and phytoremediation (Berefield et al. 1982; Liu and Liptak 2000; Henze 2001; Harvey et al. 2002; Chen 2004; Forgacs et al. 2004; Anjaneyulu et al. 2005; Crini and Badot 2007; Cox et al. 2007; Hai et al. 2007; Barakat 2011; Rathoure and Dhatwalia 2016; Morin-Crini and Crini 2017). Which is the best method? There is no direct answer to this question because each treatment has its own advantages and constraints not only in terms of cost but also in terms of efficiency, feasibility and environmental impact. In general, elimination of pollutants is done by physical, chemical and biological means. At the present time, there is no single method capable of adequate treatment, mainly due to the complex nature of industrial effluents. In practice, a combination of different methods is often used to achieve the desired water quality in the most economical way.

This short review proposes a general scheme of wastewater treatment and summarizes the advantages and disadvantages of different individual techniques used. This article is an abridged version of the chapter published by Crini and Lichtfouse (2018) in the series Environmental Chemistry for a Sustainable World.

Wastewater treatment

There are various sources of water contamination, e.g., households, industry, mines and infiltration, but one of the greatest remains the large-scale use of water by industry (Anjaneyulu et al. 2005; Hai et al. 2007). Four categories of water are generally distinguished: (1) rainwater (runoff from impermeable surfaces), (2) domestic wastewater, (3) agricultural water and (4) industrial wastewaters (Crini and Badot 2007). The last group can be subdivided into cooling water, washing effluent (of variable composition) and manufacturing or process water (biodegradable and/or potentially toxic). In general, process waters (i.e., wastewaters or effluents) pose the greatest problems. Wastewaters differ significantly from drinking water sources (usually rivers, lakes or reservoirs) in one important way: The contaminant levels in most drinking water sources are quite low as compared with contaminant levels in wastewaters derived from industrial-type activities (Cooney 1999). However, their toxicity depends, of course, on their composition, which in turn depends on their industrial origin. In general, the problems encountered during wastewater treatment are very complex as the effluent contains pollutants of various types depending on its origin. So, there are different types of effluents to treat, each with its own characteristics requiring specific treatment processes.

General scheme of wastewater treatment

When water is polluted and decontamination becomes necessary, the best purification approach should be chosen to reach the decontamination objectives (as established by legislation). A purification process generally consists of five successive steps as described in Fig. 1: (1) preliminary treatment or pre-treatment (physical and mechanical); (2) primary treatment (physicochemical and chemical); (3) secondary treatment or purification (chemical and biological); (4) tertiary or final treatment (physical and chemical); and (5) treatment of the sludge formed (supervised tipping, recycling or incineration). In general, the first two steps are gathered under the notion of pre-treatment or preliminary step, depending on the situation (Anjaneyulu et al. 2005; Crini and Badot 2007, 2010).

Technologies available for contaminant removal

In general, conventional wastewater treatment consists of a combination of physical, chemical and/or biological processes and operations to remove solids including colloids, organic matter, nutrients, soluble contaminants (metals, organics, etc.) from effluents. A multitude of techniques classified in conventional methods, established recovery processes and emerging removal methods can be used (Fig. 2). Table 1 lists the advantages and disadvantages of different individual techniques (Berefield et al. 1982; Henze 2001; Sonune and Ghate 2004; Chen 2004; Pokhrel and Viraraghavan 2004; Parsons 2004; Anjaneyulu et al. 2005; Chuah et al. 2005; Crini 2005, 2006; Bratby 2006; Crini and Badot 2007, 2010; Cox et al. 2007; Mohan and Pittman 2007; Hai et al. 2007; Wojnárovits and Takács 2008; Barakat 2011; Sharma and Sanghi 2012; Rathoure and Dhatwalia 2016; Morin-Crini and Crini 2017).

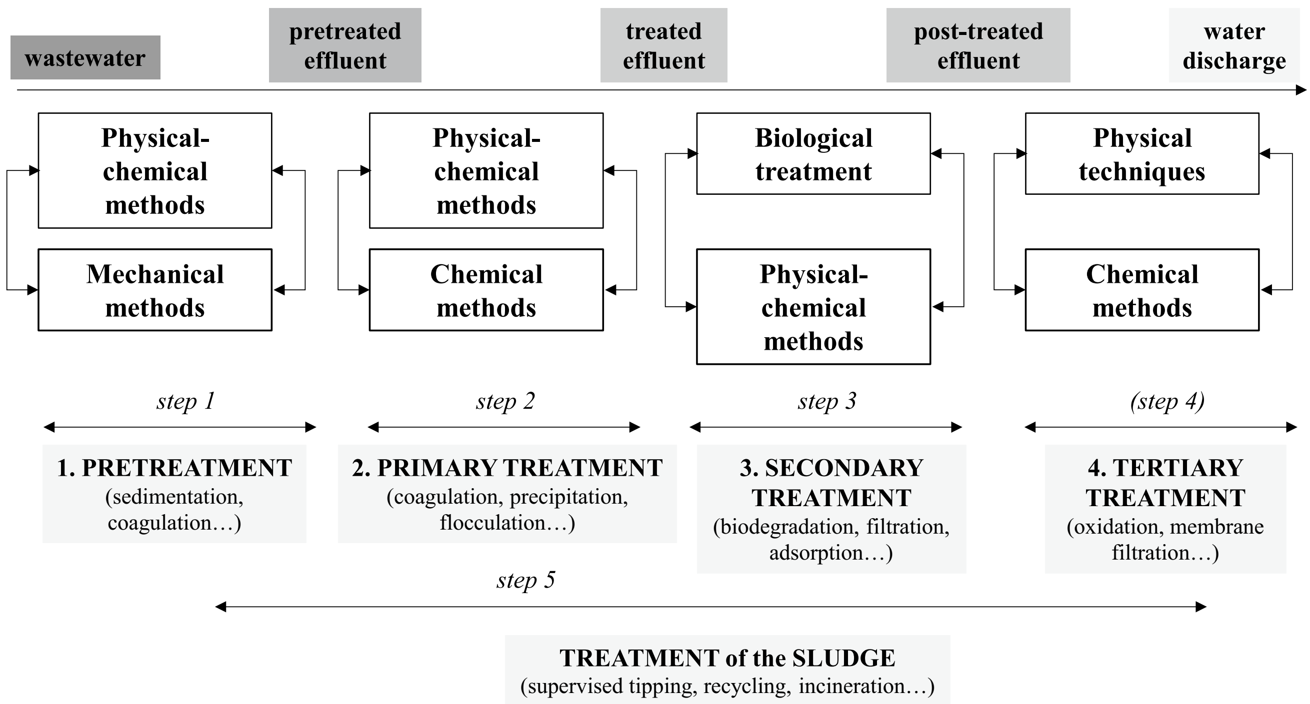

Fig. 1 Main processes for the decontamination of industrial wastewaters

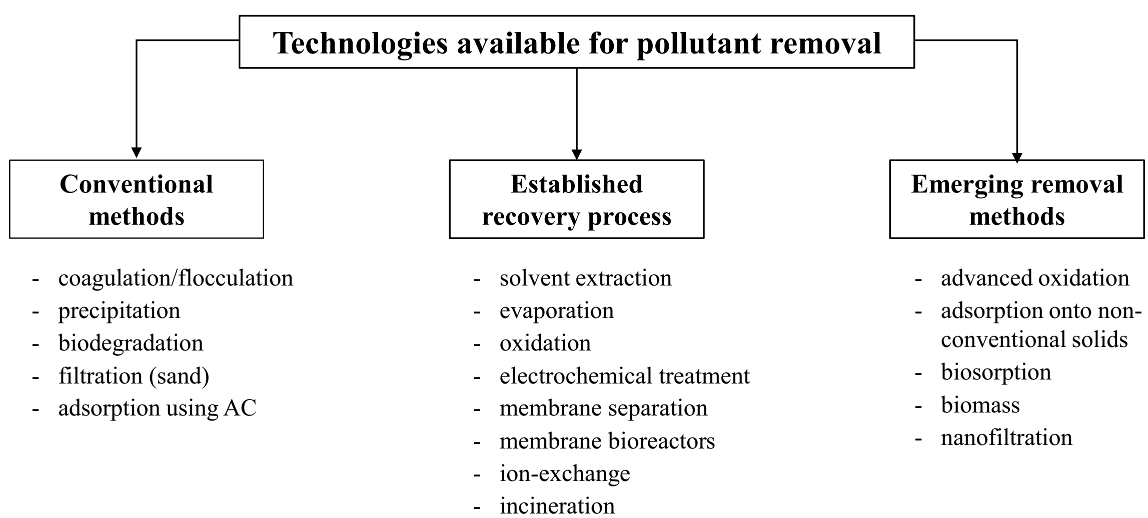

Fig. 2 Classification of technologies available for pollutant removal and examples of techniques

Selection of the method to be used will thus depend on the wastewater characteristics (Anjaneyulu et al. 2005; Crini 2005; Crini and Badot 2007; Cox et al. 2007). Each treatment has its own constraints not only in terms of cost, but also in terms of feasibility, efficiency, practicability, reliability, environmental impact, sludge production, operation difficulty, pre-treatment requirements and the formation of potentially toxic by-products. However, among the various treatment processes currently cited for wastewater treatment, only a few are commonly employed by the industrial sector for technological and economic reasons. In general, removal of pollutants from effluents is done by physicochemical and/or biological means, with research concentrating on cheaper effective combinations of systems or new alternatives.

Table 1 Advantages and disadvantages of the main conventional methods used for the treatment of polluted industrial wastewater

Process	Main characteristic(s)	Advantages	Disadvantages
Chemical precipitation	Uptake of the pollutants and separation of the products formed	Technologically simple (simple equipment) Integrated physicochemical process Both economically advantageous and efficient Adapted to high pollutant loads Very efficient for metals and fluoride elimination Not metal selective Significant reduction in the chemical oxygen demand	Chemical consumption (lime, oxidants, H_2S, etc.) Physicochemical monitoring of the effluent (pH) Ineffective in removal of the metal ions at low concentration Requires an oxidation step if the metals are complexed High sludge production, handling and disposal problems (management, treatment, cost)
Coagulation/flocculation	Uptake of the pollutants and separation of the products formed	Process simplicity Integrated physicochemical process A wide range of chemicals are available commercially Inexpensive capital cost Very efficient for SS and colloidal particles Good sludge settling and dewatering characteristics Significant reduction in the chemical oxygen demand and biochemical oxygen demand Interesting reduction in total organic carbon and adsorbable organic halogen (pulp and paper industry) Bacterial inactivation capability Rapid and efficient for insoluble contaminants (pigments, etc.) removal	Requires adjunction of non-reusable chemicals (coagulants, flocculants, aid chemicals) Physicochemical monitoring of the effluent (pH) Increased sludge volume generation (management, treatment, cost) Low removal of arsenic
Flotation Froth flotation	Separation process	Integrated physicochemical process Different types of collectors (nonionic or ionic) Efficient for removal of small particles and can remove low-density particles which would require long settling periods Useful for primary clarification Metal selective Low retention time Used as an efficient tertiary treatment in the pulp and paper industry Mechanisms: true flotation, entrainment and aggregation	High initial capital cost Energy costs Maintenance and operation costs no negligible Chemicals required (to control the relative hydrophobicities between the particles and to maintain proper froth characteristics) Selectivity is pH dependent

Table 1 (continued)

Process	Main characteristic(s)	Advantages	Disadvantages
Chemical oxidation Simple oxidation Ozone Hypochlorite treatment Hydrogen peroxide	Use of an oxidant (e.g., O_3, Cl_2, ClO_2, H_2O_2, $KMnO_4$)	Integrated physicochemical process Simple, rapid and efficient process Generation of ozone *on-site* (no storage-associated dangers) Quality of the outflow (effective destruction of the pollutants and efficient reduction in color) Good elimination of color and odor (ozone) Efficient treatment for cyanide and sulfide removal Initiates and accelerates azo bond cleavage (hypochlorite treatment) Increases biodegradability of product High throughput No sludge production Possibility of water recycle Disinfection (bacteria and viruses)	Chemicals required Production, transport and management of the oxidants (other than ozone) Pre-treatment indispensable Efficiency strongly influenced by the type of oxidant Short half-life (ozone) A few dyes are more resistant to treatment and necessitate high ozone doses Formation of (unknown) intermediates No diminution of chemical oxygen demand values or limited effect (ozone) No effect on salinity (ozone) Release of volatile compounds and aromatic amines (hypochlorite treatment) Generates sludge
Biological methods Bioreactors Biological activated sludge (BAS) Microbiological treatments Enzymatic decomposition Lagoon	Use of biological (pure or mixed) cultures	The application of microorganisms for the biodegradation of organic contaminants is simple, economically attractive and well accepted by the public Large number of species used in mixed cultures (consortiums) or pure cultures (white-rot fungus) White-rot fungi produce a wide variety of extracellular enzymes with high biodegradability capacity Efficiently eliminates biodegradable organic matter, NH_3, NH_4^+, iron Attenuates color well High removal of biochemical oxygen demand and suspended solids (BAS) Decisive role of microbiological processes in the future technologies used for the removal of emergent contaminants from waters	Necessary to create an optimally favorable environment Requires management and maintenance of the microorganisms and/or physicochemical pre-treatment (inefficient on non-degradable compounds or when toxic compounds are present) Slow process (problems of kinetics) Low biodegradability of certain molecules (dyes) Poor decolorization (BAS) Possible sludge bulking and foaming (BAS) Generation of biological sludge and uncontrolled degradation products The composition of mixed cultures may change during the decomposition process Complexity of the microbiological mechanisms Necessity to have a good knowledge of the enzymatic processes governing the decomposition of the substances

Table 1 (continued)

Process	Main characteristic(s)	Advantages	Disadvantages
Adsorption/filtration Commercial activated carbons (CAC) Commercial activated alumina (CAA) Sand Mixed materials Silica gel	Nondestructive process Use of a solid material	Technologically simple (simple equipment) and adaptable to many treatment formats Wide range of commercial products Wide variety of target contaminants (adsorption) Highly effective process (adsorption) with fast kinetics Excellent quality of the treated effluent Global elimination (CAC) but possibly selective depending on adsorbent Excellent ability to separate a wide range of pollutants, in particular refractory molecules (CAC is the most effective material) CAC: efficient for chemical oxygen demand removal; highly efficient treatment when coupled to coagulation to reduce suspended solids, chemical oxygen demand and color Sand: efficient for turbidity and suspended solids removal Alumina: efficient for fluoride removal	Relatively high investment (CAC) Cost of materials (CAC, CAA) Nondestructive processes Non-selective methods Performance depends on the type of material (CAC) Requirement for several types of adsorbents Chemical derivatization to improve their adsorption capacity Rapid saturation and clogging of the reactors (regeneration costly) Not efficient with certain types of dyestuffs and some metals (CAC) Elimination of the adsorbent (requires incineration, regeneration or replacement of the material) Regeneration is expensive and results in loss of material (CAC) Economically non-viable for certain industries (pulp and paper, textile, etc.)
Ion exchange Chelating resins Selective resins Macroporous resins Polymeric adsorbents Polymer-based hybrid adsorbents	Nondestructive process	Wide range of commercial products available from several manufacturers Technologically simple (simple equipment) Well-established and tested procedures; easy control and maintenance Easy to use with other techniques (e.g., precipitation and filtration in an integrated wastewater process) Can be applied to different flow regimes (continuous and batch) High regeneration with possibility of external regeneration of resin Rapid and efficient process Produce a high-quality treated effluent Concentrates all types of pollutants, particularly minerals Relatively inexpensive and efficient for metal removal; cleanup to ppb levels (to ppt levels for selective resins) Can be selective for certain metals (with suitable resins) Interesting and efficient technology for the recovery of valuable metals	Economic constraints (initial cost of the selective resin, maintenance costs, regeneration time-consuming, etc.) Large volume requires large columns Rapid saturation and clogging of the reactors Saturation of the cationic exchanger before the anionic resin (precipitation of metals and blocking of reactor) Beads easily fouled by particulates and organic matter (organics and oils); requires a physico-chemical pre-treatment (e.g., sand filtration or carbon adsorption) to remove these contaminants Matrix degrades with time and with certain waste materials (radioactive, strong oxidants, etc.) Performance sensitive to pH of effluent Conventional resins not selective Selective resins have limited commercial use Not effective for certain target pollutants (disperse dyes, drugs, etc.) Elimination of the resin

Table 1 (continued)

Process	Main characteristic(s)	Advantages	Disadvantages
Incineration Thermal oxidation Catalytic oxidation Photocatalytic destruction	Destruction by combustion	Simple process Useful for concentrated effluents or sludges Highly efficient Eliminates all types of organics Production of energy	Initial investment costs Transport and storage of the effluents High running costs Formation of dioxins and others pollutants (metals, etc.) Local communities always have opposed the presence of incinerating plant in the locality
Electrochemistry Electrodeposition Electro-coagulation (EC) Electro-flocculation (EF) Electro-flotation Electro-oxidation Electrochemical oxidation Electrochemical reduction Cementation Indirect electro-oxidation with strong oxidants Photo-assisted electrochemical methods	Electrolysis (E)	Efficient technology for the recovery/recycling of valuable metals (E); interesting method for the recovery of gold and silver from rinse baths Adaptation to different pollutant loads and different flow rates (E) Increases biodegradability (E) More effective and rapid organic matter separation than in traditional coagulation (EC); pH control is not necessary; generation of coagulants in situ; economically feasible and very effective in removing suspended solids, dissolved metals, tannins and dyes (effluents from textile, catering, petroleum, municipal sewage, oil–water emulsion, dyestuff, clay suspension, etc.) Efficient elimination of SS, oils, greases, color and metals (EC, EF) EF: widely used in the miming industries Effective in treatment of drinking water supplies for small- or medium-sized communities (EC) Very effective treatment for the reduction, coagulation and separation of copper (EC) Cementation: efficient for copper removal	High initial cost of the equipment Cost of the maintenance (sacrificial anodes, etc.) Requires addition of chemicals (coagulants, flocculants, salts) Anode passivation and sludge deposition on the electrodes that can inhibit the electrolytic process in continuous operation Requires post-treatment to remove high concentrations of iron and aluminum ions EF: separation efficiency depends strongly on bubble sizes Filtration process for flocs Formation of sludge (filtering problems) Cost of sludge treatment (electro-coagulation)

Table 1 (continued)

Process	Main characteristic(s)	Advantages	Disadvantages
Membrane filtration Microfiltration (MF) Ultrafiltration (UF) Nanofiltration (NF) Reverse osmosis Dialysis Electrodialysis (ED) Electro-electrodialysis (EED) Emulsion liquid membranes (ELM) Supported liquid membranes	Nondestructive separation Semipermeable barrier	Wide range of commercial membrane available from several manufacturers; large number of applications and module configurations Small space requirement Simple, rapid and efficient, even at high concentrations Produces a high-quality-treated effluent No chemicals required Low solid waste generation Eliminates all types of dyes, salts and mineral derivatives Efficient elimination of particles, suspended solids and microorganisms (MF, UF, NF, reverse osmosis), volatile and nonvolatile organics (NF, reverse osmosis), dissolved inorganic matter (ED, EED), and phenols, cyanide and zinc (ELM) Possible to be metal selective A wide range of real applications: clarification or sterile filtration (MF), separation of polymers (UF), multivalent ions (NF), salts from polymer solutions (dialysis) and nonionic solutes (ED), desalination and production of pure water (reverse osmosis) Well-known separation mechanisms: size-exclusion (NF, UF, MF), solubility/diffusivity (reverse osmosis, pervaporation), charge (electrodialysis)	Investment costs are often too high for small and medium industries High energy requirements The design of membrane filtration systems can differ significantly High maintenance and operation costs Rapid membrane clogging (fouling with high concentrations) Low throughput Limited flow rates Not interesting at low solute feed concentrations The choice of the membrane is determined by the specific application (hardness reduction, particulate or total organic carbon removal, potable water production, etc.) Specific processes Elimination of the concentrate

Table 1 (continued)

Process	Main characteristic(s)	Advantages	Disadvantages
Evaporation Membrane pervaporation	Concentration technique Thermal process Separation process	Several types of evaporators exist on the market Versatile technique (the number of cells can be adapted to the required evaporation capacity) The energy costs are well known for the different configurations Efficient processes Interesting for the production of water for rinsing operations (recycling of distillates), the concentration of rinsing effluents for re-introduction into the process and for the purification of treatment baths (to maintain their nominal concentration) Also interesting for the separation of phenol by steam distillation Membrane pervaporation: a quite recent technology applied to the removal of organics from water	Expensive costs for high volumes of wastewater (energy consumption, volume of the concentrate and costs of disposal) Investment costs are often too high for small and medium industries High pollution load in the concentrates Crystallization due to the concentration of the wastewater and corrosion of the heating elements in the evaporator due to the chemical aggressiveness of the concentrated effluent Problem with the evaporation of effluents containing free cyanide Requires the installation of a cleaning circuit (to prevent atmospheric pollution) Potential contamination of the distillate preventing reuse (due to the presence of some volatile organic compounds or hydrocarbons in the effluent)
Liquid–liquid (solvent) extraction Membrane-based solvent extraction	Separation technology Solvent extraction	A well-known established separation technology for wastewater recycling Principally used for large-scale operations where the load of contaminants are high Extraction/stripping operations easy to perform Simple control and monitoring of process Economically viable when both solute concentrations and wastewater flow rates are high Relatively low operating costs Recyclability of extractants Selectivity of the exchangers for metals efficient for metal removal (cations, anions, ion pairs) Efficient for the separation of phenol A good alternative to classical lime precipitation for phosphoric acid recuperation	High investment (equipment) Uneconomic when contaminant concentrations are low (<0.5 g/L) Use of large volumes of organic extractants Use of potential toxic solvents Not interesting at low solute feed concentrations Hydrodynamic constraints (flooding and entrainment) Entrainment of phases giving poor effluent quality Possible cross-contamination of the aqueous stream Emulsification of phase with poor separation Fire risk from use of organic solvents and volatile organic compounds emissions

Table 1 (continued)

Process	Main characteristic(s)	Advantages	Disadvantages
Advanced oxidation processes (AOP) Photolysis Heterogeneous and homogeneous photocatalytic reactions Non-catalytic wet air oxidation (WAO) Catalytic wet air oxidation (CWAO) Supercritical water gasification	Emerging processes Destructive techniques	In situ production of reactive radicals Little or no consumption of chemicals Mineralization of the pollutants No production of sludge Rapid degradation Efficient for recalcitrant molecules (dyes, drugs, etc.) Very good abatement of chemical oxygen demand and total oxygen demand WAO: technology suitable for effluent too dilute for incineration and too toxic and/or concentrated for biological treatment Destruction of phenol in water solution: WAO, CWAO Insoluble organic matter is converted to simpler soluble compounds without emissions of dangerous substances (WAO)	Laboratory scale Economically non-viable for small and medium industries Technical constraints Formation of by-products Low throughput High-pressure and energy-intensive conditions (WAO) pH dependence (in particular for WAO) WAO: completed mineralization not achieved

Conclusion

The development of cheaper, effective and novel methods of decontamination is currently an active field of research, as shown by the numerous publications appearing each year. Preserving the environment, and in particular the problem of water pollution, has become a major preoccupation for everyone—the public, industry, scientists and researchers as well as decision-makers on a national, European or international level. The public demand for pollutant-free waste discharge to receiving waters has made decontamination of industrial wastewaters a top priority. However, this is a difficult and challenging task (Sonune and Ghate 2004; Anjaneyulu et al. 2005; Crini 2005; Crini and Badot 2007; Barakat 2011; Sharma and Sanghi 2012). It is also difficult to define a universal method that could be used for the elimination of all pollutants from wastewaters. This review described the advantages and disadvantages of technologies available. A multitude of techniques classified in conventional methods, established recovery processes and emerging removal methods can be used. However, among the numerous and various treatment processes currently cited for wastewater treatment, only a few are commonly used by the industrial sector for economic and technological reasons. Adsorption onto activated carbons is nevertheless often cited as the procedure of choice to remove many different types of pollutants because it gives the best results in terms of efficiency and technical feasibility at the industrial scale.

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